Numerical simulations of transitional flows using γ-SST model

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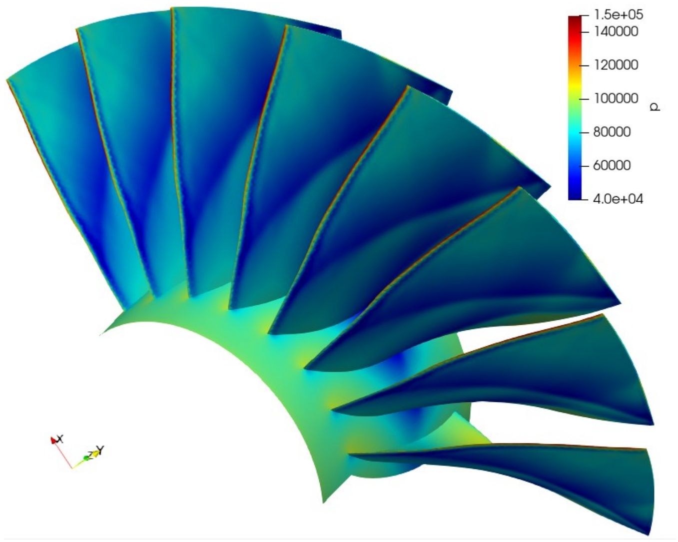
Introduction

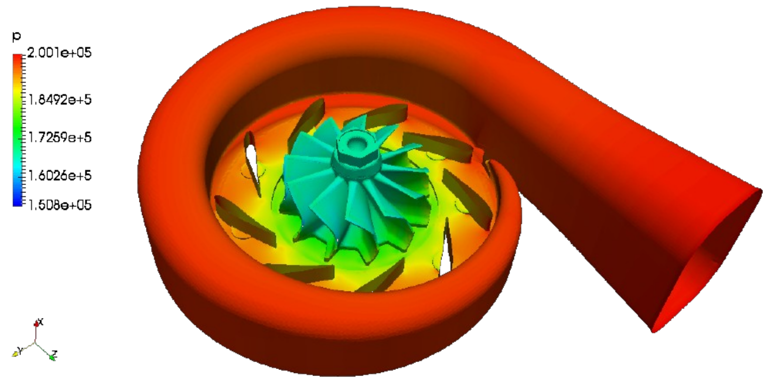
<u>Turbomachinery flows:</u>

- High speed, compressible internal flows
- Transonic regimes, shock waves, …
- Rotating system, multiple frames of reference,
- Specific boundary conditions (stator-rotor interfaces, non-reflecting boco, …)
- Complicated physics (EOS, non-equilibrium condensation of steam, …)
- Surface roughness



<u>Typical flow regimes:</u>

- Ma = 0.5 – 2
- Re ~ 10^6
- Tu = 2 – 10%
- Bypass transition



Mean flow solver

OpenFOAM package

- An open source framework for finite-volume method
- Contains several ready made solvers for incompressible flows, heat transfer, …
- OpenFOAM solvers for high-speed compressible flows:
  - *rhoSimpleFoam* – segregated, very "fragile", sensitive to under-relaxation, …
  - *rhoCentralFoam* – coupled, explicit time stepping (not suitable for Low-Re approach)

In-house solver [1]

- Built on top of OpenFOAM package
- standard FVM with convective fluxes evaluated using approximate Riemann solvers (HLLC with low-Mach correction [2])
- Second order in space using piece-wise linear reconstructions with limiters
- Implicit time stepping with matrix-free LU-SGS method
- Weak coupling with transition and turbulence model:
  1. Update mean flow variables (ρ, U, E) using old values of turbulence variables ($k, \omega, \gamma, \ldots$)
  2. Update turbulence model using new mean flow variables (with under-relaxation)

Solver available at: https://github.com/furstj/myFoam

[1] FÜRST, Jiří. *Development of a coupled matrix-free LU-SGS solver for turbulent compressible flows. Computers & Fluids. August 2018. Vol. 172, p. 332–339. DOI 10.1016/j.compfluid.2018.04.020.*

[2] XIE, Wenjia, ZHANG, Ran, LAI, Jianqi and LI, Hua. *An accurate and robust HLLC-type Riemann solver for the compressible Euler system at various Mach numbers. International Journal for Numerical Methods in Fluids. 2019. DOI 10.1002/fld.4704.*

Transition and turbulence model

γ-SST model [3]

- Local correlation based model, similar to Langtry's & Menter's γ-Re_θ model with Re_θ equation replaced by an algebraic relation
- γ equation is coupled to SST model with P_k calculated using Kato-Launder modification
- Contains additional source term for transition at low Tu and for transition in separated flows [3]
- Missing: reliable cross-flow transition, compressibility effects, …

k-kL-ω model [4]

- Three-equation laminar kinetic energy model
- Suitable for bypass and natural transition
- Missing: separation induced transition, cross-flow transition, compressibility effects, …

Both models available as an additional library for OpenFOAM at:
https://github.com/furstj/myTurbulenceModels

[3] MENTER, Florian R., SMIRNOV, Pavel E., LIU, Tao and AVANCHA, Ravikanth. A one-equation local correlation-based transition model. Flow, Turbulence and Combustion. 5 December 2015. Vol. 95, no. 4, p. 583–619. DOI 10.1007/s10494-015-9622-4

[4] LOPEZ, Maurin and KEITH WALTERS, D. A Recommended Correction to the $k_T - k_L - \omega$ Transition-Sensitive Eddy-Viscosity Model. Journal of Fluids Engineering [online]. 7 December 2016. Vol. 139, no. 2, p. 024501. DOI 10.1115/1.4034875.

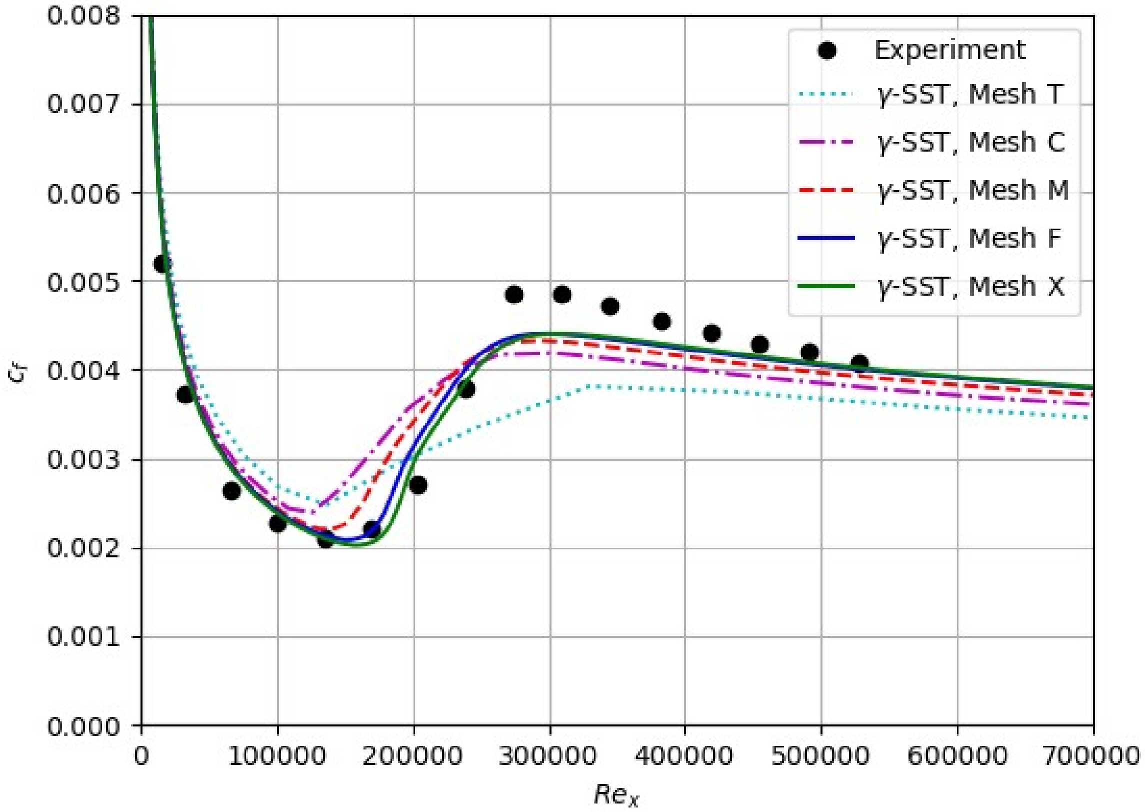
Results: Flat plate flows

Case 1A

Computation:
- Tu = 5.86% (at inlet)
- μ_t/μ = 11.9

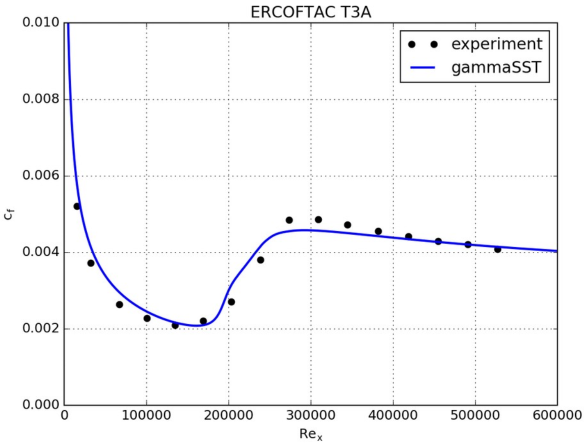
Experiment (ERCOFTAC)
- Tu = 3.3% (at LE)

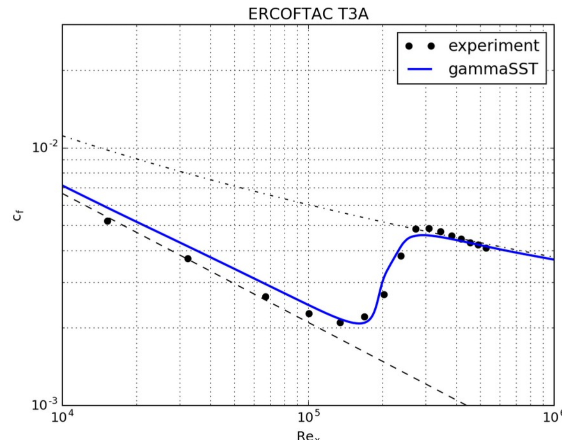
Mesh	# cells	y^+
Tiny	1 056	1.50
Coarse	4 224	0.68
Medium	16 896	0.32
Fine	67 584	0.16
eXtra f.	270 336	0.08

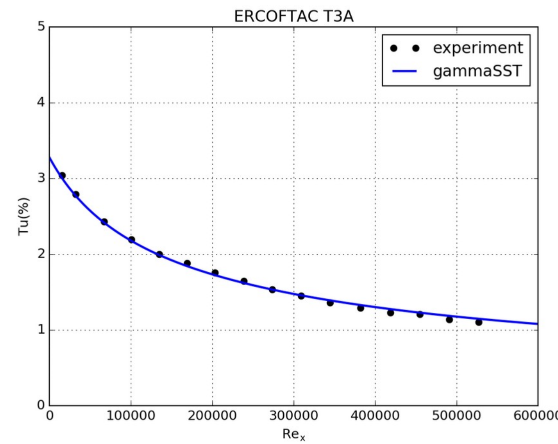


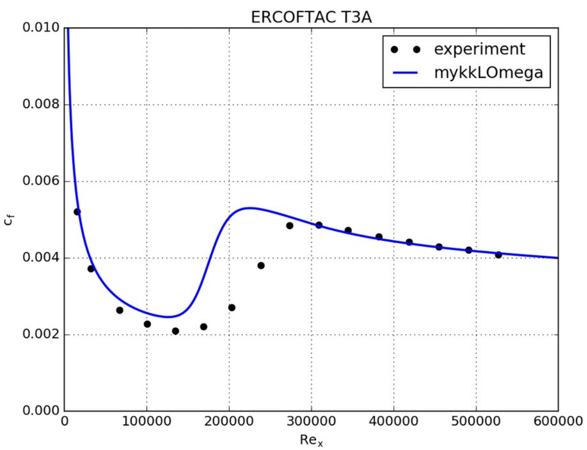
Results: Flat plate flows

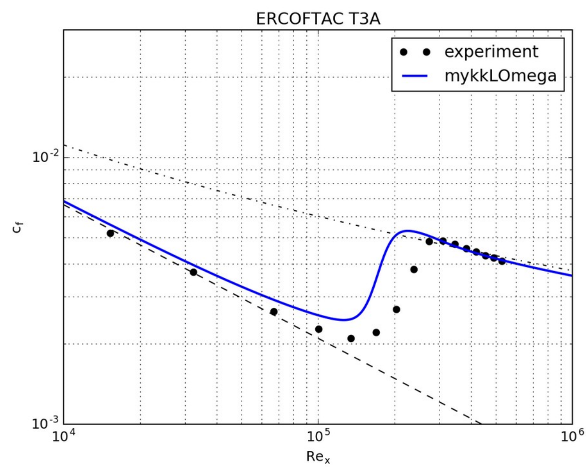
Case 1A, custom mesh & BC











Mesh:

- 66 675 cells,
- $y^+ \sim 0.2$,
- similar to mesh F

Incompressible fluid

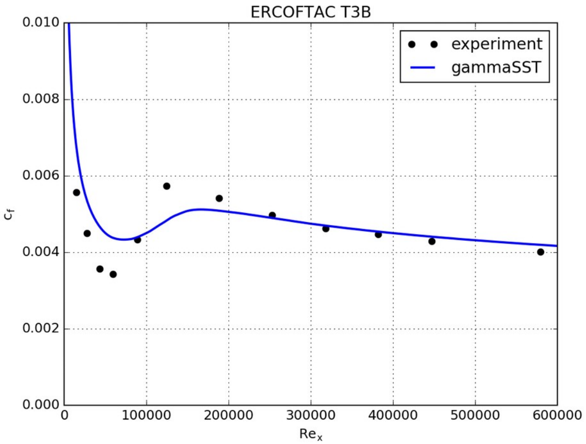
SIMPLE algorithm

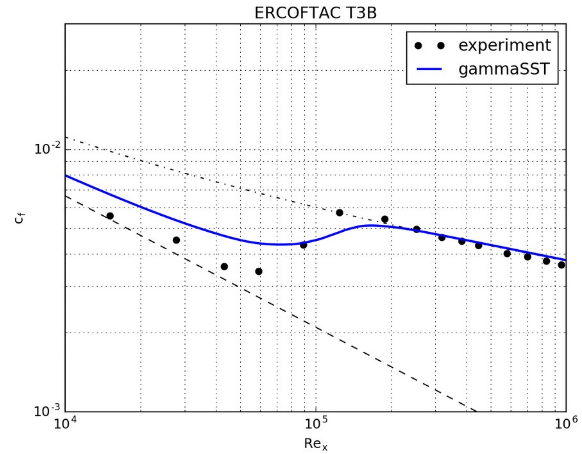
Tu = 3.7%

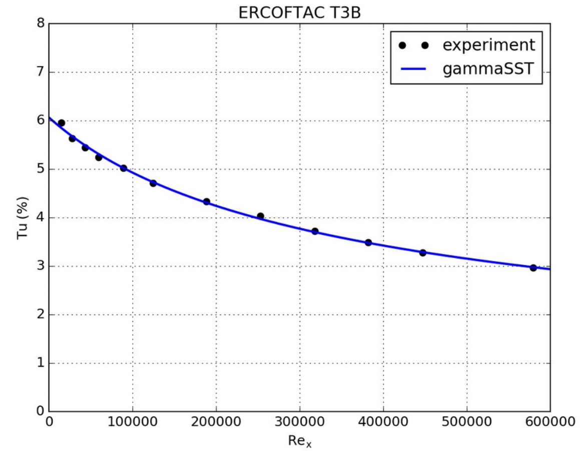
$\nu_t/\nu = 12.3$ (for γ-SST)

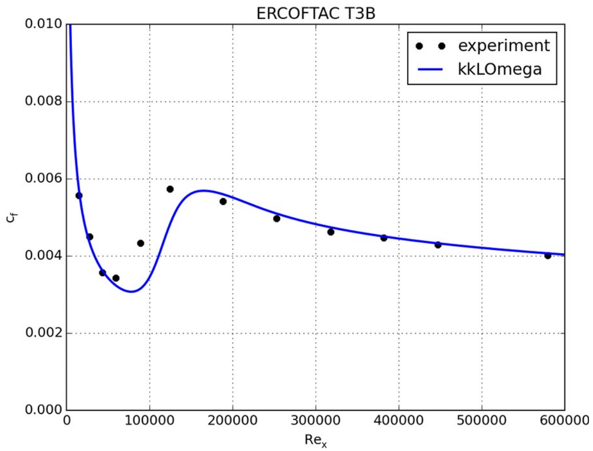
Results: Flat plate flows

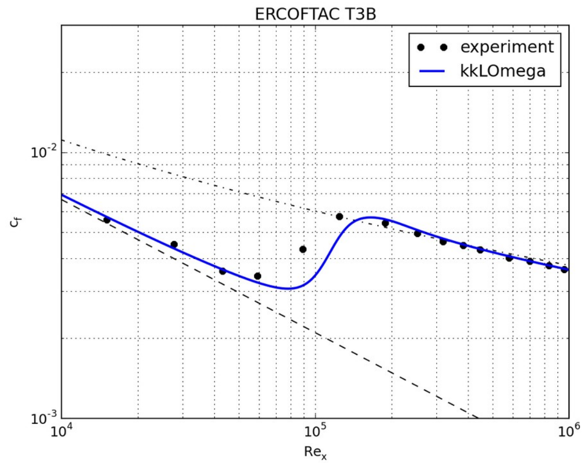
Case 1B, custom mesh & BC











Mesh:

- 66 675 cells,
- $y^+ \sim 0.2$,
- similar to mesh F

Incompressible fluid

SIMPLE algorithm

Tu = 6.6 %

$\nu_t/\nu = 100$ (for γ-SST)

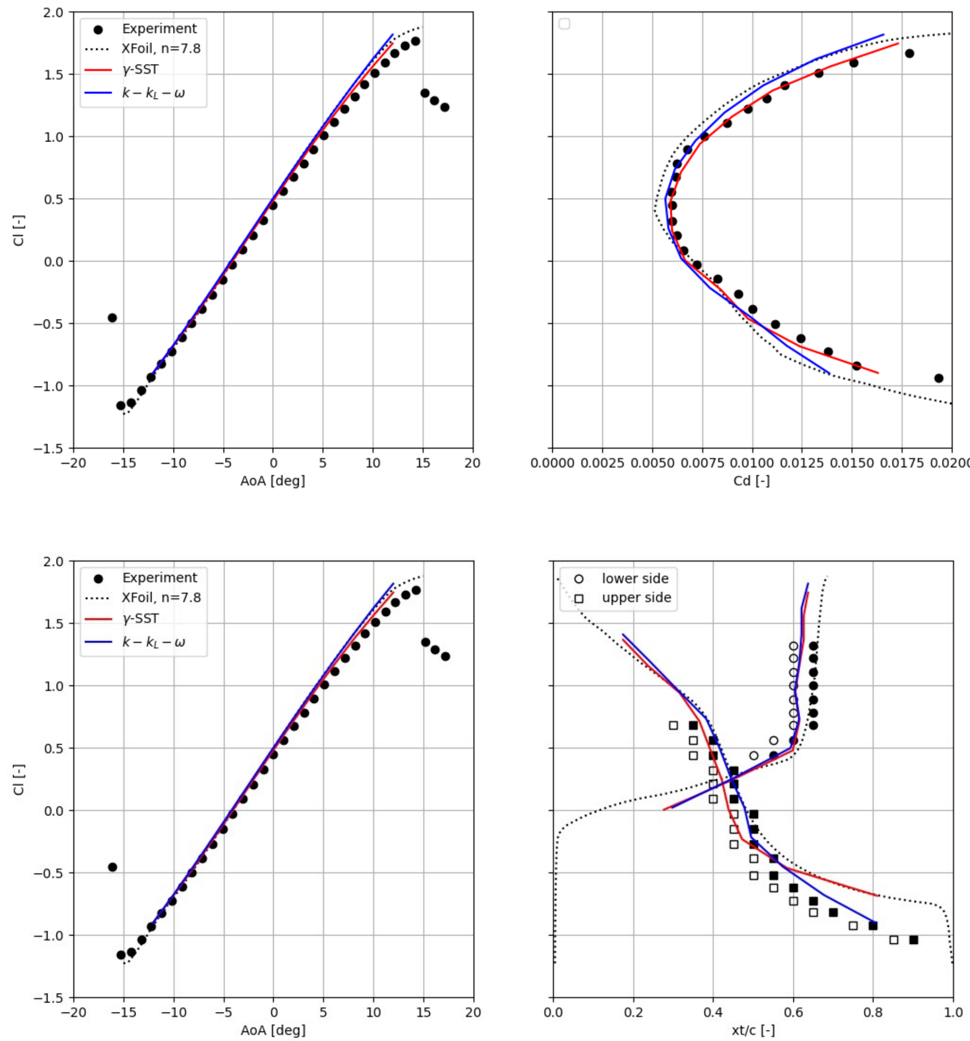
Results: NLF(1)-0416

Data for Tu=0.15% : submitted TWS

Here: data for
- Re = 4 000 000
- M = 0.1
- Tu = 0.11%
- ω_∞ = 5 U / chord

Mesh:
- 67 584 cells
- y^+ ~ 0.2

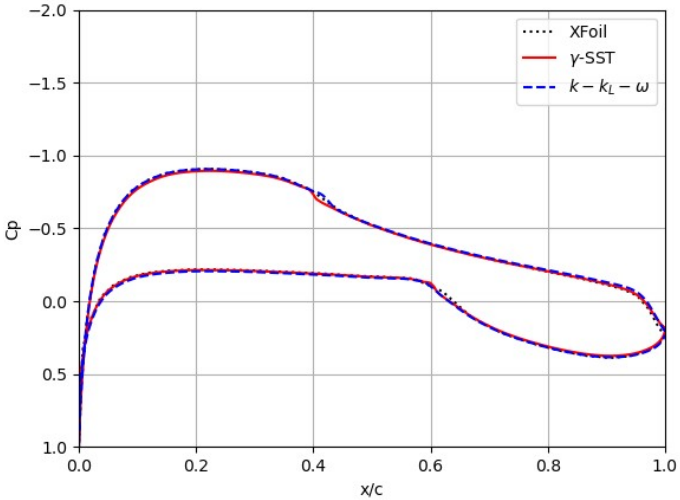
Comparison with:
- XFoil (n = 7.8)
- Experimental data [5]

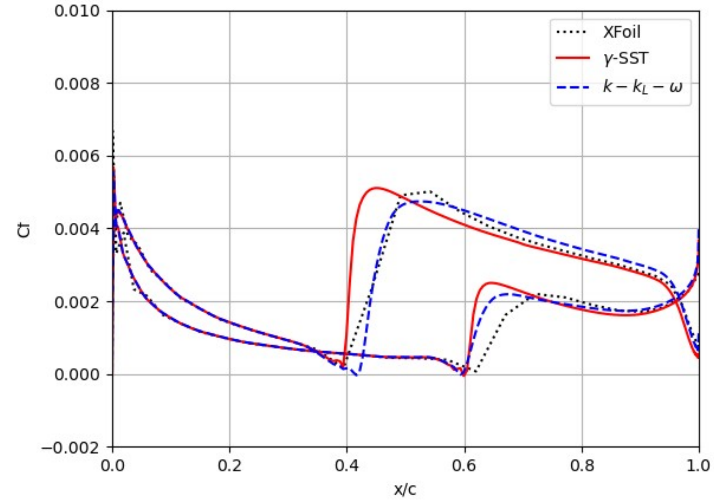


[5] Somers D.: Design and experimental results for a natural laminar flow airfoil for general aviation applications, NASA-TP-1861, 1981

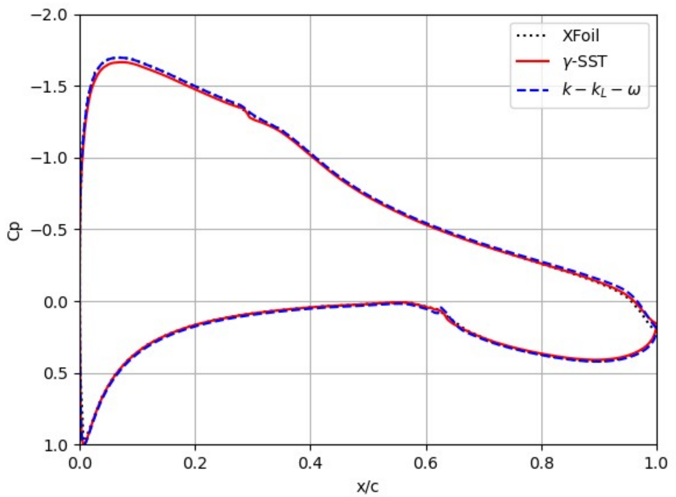
Results: NLF(1)-0416

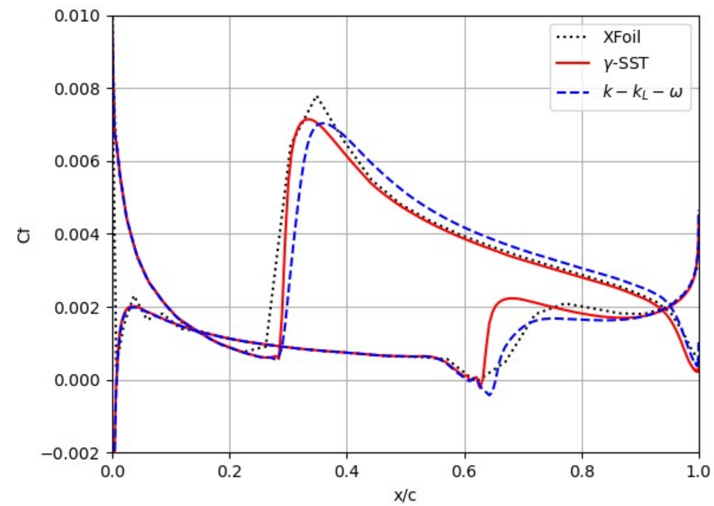
AoA = 0°





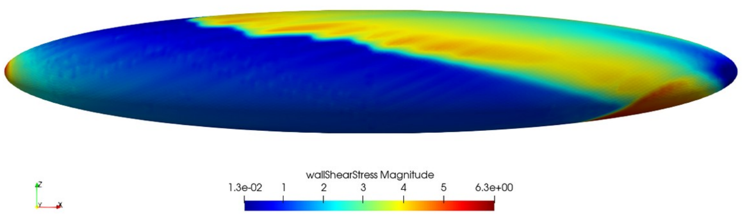
AoA = 5°

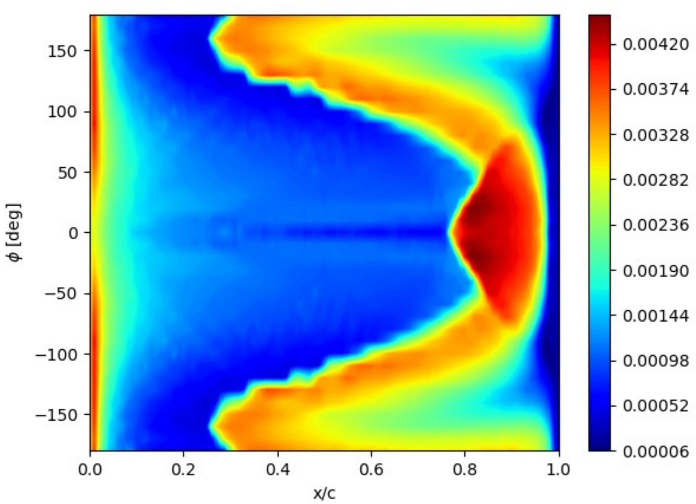




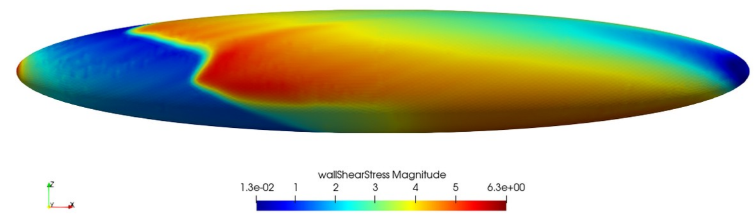
Results: Ellipsoid

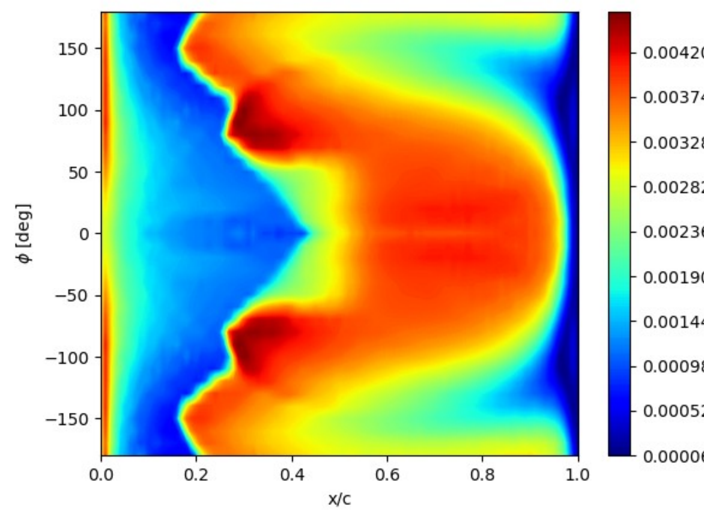
Case 3, AoA = 10^{o}





without CF correlation





with CF correlation (C1)

Results: Case 4

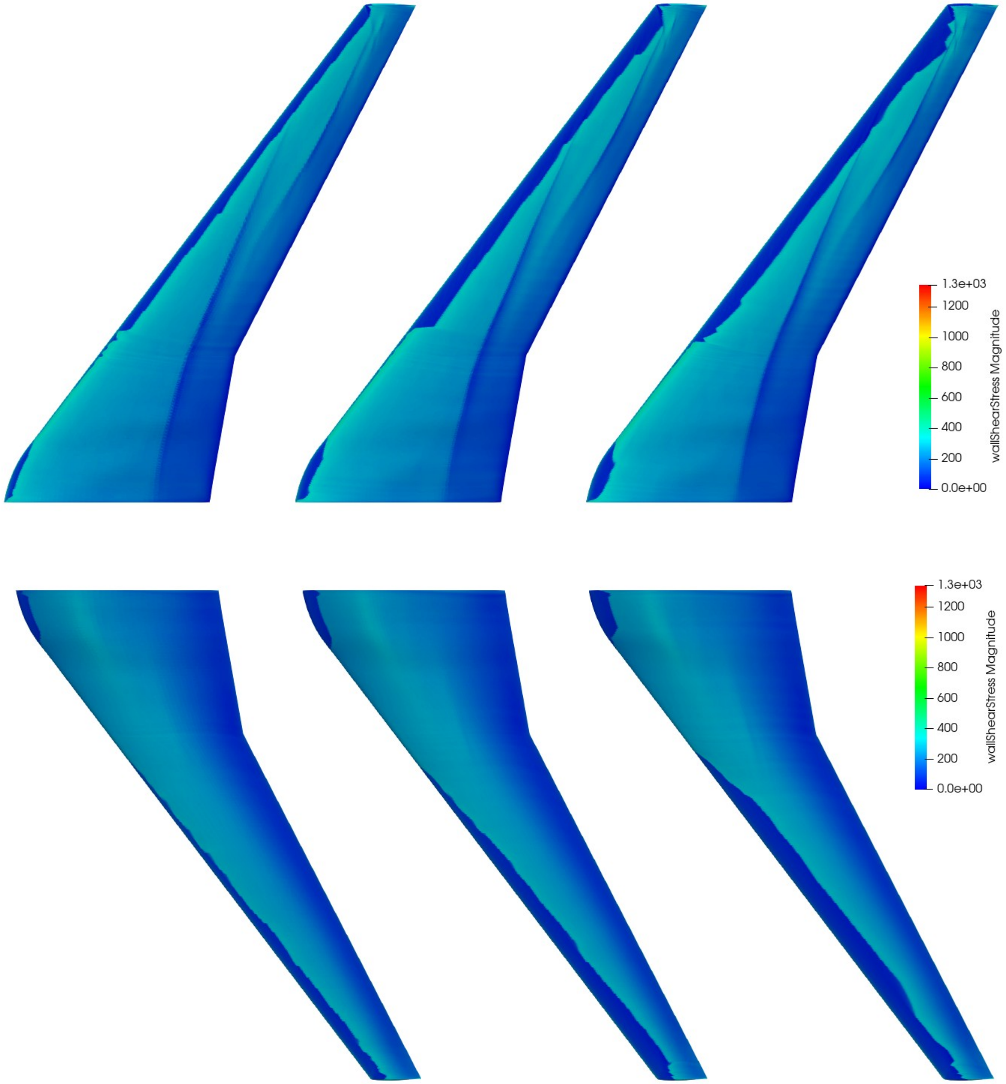
AoA = 1.98^{o}

- Unstructured mesh (Series A)
- gamma-SST model
- No CF correlation
- No sustaining term

<u>Meshes:</u>

8 – 7 mil. elems
12 – 20 mil. elems
16 – 46 mil. elems

Mesh	Cl	Cd
8	0.3826	0.0234
12	0.3859	0.0220
16	0.3890	0.0215



Mesh 8 Mesh 12 Mesh 16

Conclusion

<u>Results obtained with γ-SST model</u>

- Case 1 & 2 – quite good results consistent with experiment and other models
- Case 3 (ellipsoid) – very bad results due to missing CF correlation

- The γ-SST model needs improvements for
  - cross-flow transition (C1 is valid only for wings)
  - compressibility, shock-wave BL interaction,
  - transition due to distributed roughness (some work already done for γ-Re_θ by Dassler et al. or Langel et al.)

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